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NAP-100 THERMOELECTRIC GENERATOR REPORT

TECHNICAL DOCUMENTARY REPORT NO. AFSWC-TDR-61-99
November 1961

Development Directorate
AIR FORCE SPECIAL WEAPONS CENTER
Air Force Systems Command
Kirtland Air Force Base
New Mexico

Project No. 6185, Task No. 618503

(Prepared under Contract No. AF 30(602)-1875 by G. Spira and T. M. Corry, Westinghouse Electric Corporation, New Products Laboratories, Cheswick, Pennsylvania) N-62-3-1

ACKNOWLEDGMENT

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ABSTRACT

This report describes the development and performance of a 100-watt thermoelectric generator designated NAP-100 (Nuclear Auxiliary Power). The work was performed for the US Air Force under Contract No. AF 30(602)-1875. The delivery of the generator fulfills the second phase of the contract which required the development and construction of an isotopic fuel thermoelectric generator rated at 100 watts electrical output.

Construction details and generator performance data are given in this report for the NAP-100 generator. The generator was delivered on December 7, 1960, and tested at the Air Force Special Weapons Center.

PUBLICATION REVIEW

This report has been reviewed and is approved.

M. E. Sorte
M. E. SORTE
Colonel USAF
Director, Development Directorate

Tyler A. Redfield
FOR AND IN THE ABSENCE OF
JOHN J. DISHUCK
Colonel USAF
Deputy Chief of Staff for Operations

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INTRODUCTION

The subject of this report is a thermoelectric generator which was designed to utilize an isotopic heat source and natural convective cooling. The generator was built and developed under contract with the Rome Air Development Center. The administration of the contract was transferred to Air Force Special Weapons Center (AFSWC) on 9 September 1960. At Westinghouse, the power output was 130 watts at 10 volts. In the design of this thermoelectric generation device, weight, size, need for logistical support and maintenance were considered as important factors in the system. A view of the completed NAP-100 generator is shown in Figure 1.

The scope and purpose of this report are to outline the design concepts used and to describe the development work performed under the contract. In addition, the generator design and performance are described in specific detail. Drawings of the final model and the operating instructions have been supplied as separate items.

GENERATOR DEVELOPMENT AND DESIGN CONCEPTS

During the development program, the generator unit was treated as an integrated system in order to minimize size and weight without undue sacrifice in efficiency. This required a careful thermal match of three basic elements of the generator:

1) the cold side convective heat exchanger
2) the thermoelectric couple assembly
3) the heat source (an electrical heater which simulated the thermal performance of the nuclear heat source was designed and delivered with the generator)

In order to obtain this matching, extensive development work was necessary in each of the basic areas.

<u>Cold Side Heat Exchanger</u>

The development of the free-convection cooled heat exchanger basically involved the optimization of an exchanger in terms of watts dissipated per unit weight and watts dissipated per unit area. Preliminary estimates of thermoelectric couple efficiency and heat exchanger capacities indicated that the exchanger base plate would probably operate at a temperature between 140°C and 180°C.

In earlier investigations it was determined that the rectangular-pin type heat exchanger gave the highest heat dissipation per unit weight and per unit area. Comparative results given in Figure 2 for several specimens show the superior heat dissipating capacity of the rectangular pin-type heat exchanger. The final design of the heat exchanger is shown in Figure 3 and the mechanical and performance data for the equivalent test specimen are listed in Table I.

<u>Table I - Pertinent Data on Final Heat Exchanger Design</u>

Pin Size -	3-1/4" x 3/32" x 1/16"
Pin Spacing -	3/16" (between centers)
Row Spacing -	3/8"
Pin Material -	6061 Aluminum
Plate Material -	6061 Aluminum (1/4" thick)
Orientation of Rows -	Vertical
Surface Treatment -	Anodized (black)
Dissipation/Unit Weight at 150°C -	13.8 watts/oz
Dissipation/Unit Base Plate Area at 150°C -	10.8 watts/in^2

Couple Design and Development

An analysis of the properties of available thermoelectric materials indicated that the most suitable materials for use in the NAP-100 generator should operate at a hot junction temperature of 500-550°C. Original estimates of heat exchanger performance for the heat sink indicated that the cold side temperature be between 140 and 180°C for the estimated thermocouple efficiencies and power densities. A number of different test couples were designed, fabricated, and tested in the temperature ranges previously mentioned to determine their actual performance. On the basis of these tests and the results of the preliminary work on the heat source and cold side exchanger, a couple was selected for the generator. The thermoelectric materials used for this couple were PbTe for the N leg and GeBiTe for the P leg.[1]

Other major considerations affecting the couple design and the number of couples needed were:

1) the required generator output voltage
2) power output
3) efficiency

The voltage obtainable from a couple is determined by the hot and cold operating temperatures and the choice of thermoelectric materials. On this basis, it was determined that approximately 140 couples would be needed to obtain a nominal 12-volt system under load. In order to make certain that the 100-watt output would be obtained, it was decided to build the couple for a nominal 1-watt output. The actual design value for this couple was closer to 1.3 watts output, but previous test work indicated that contact resistance and other practical factors reduced actual couple performance below the theoretical value. These preceding requirements partially established the couple geometry. The specific size was determined on the basis of the thermal flux which could be drawn from the hot side core, geometries that could be produced in the pilot plant facility, and the surface area on the core available for accommodating 140 thermocouples. Power output and efficiency tests were made on this couple. In the efficiency range currently realized with thermoelectric materials, operation at maximum power transfer or at maximum efficiency is practically equivalent. Results are shown in Figures 4, 5 and 6. The final couple design is shown in Figure 7. Figure 5 shows a family of curves of thermocouple effiency versus hot junction temperature for various cold junction temperatures. The curves were made from measurements that included braid temperature drops and heat leakage through the thermal insulation that was packed between the thermoelements in an eight-couple array. Efficiency was measured under maximum power transfer conditions. Shown also in Figure 5 is a dotted curve of efficiency versus hot junction temperature for a thermoelectric material with a figure of merit $Z = 1 \times 10^{-3}/°C$. The curve was calculated from the relationship that expressed effiency as a function of figure of merit and hot and cold junction temperatures under conditions of maximum power transfer:

$$n = \frac{1}{2} \frac{T_h - T_c}{T_h + \frac{2}{Z} - \frac{1}{4}(T_h - T_c)}$$

$$\text{where} \quad Z = \frac{(S_n - S_p)^2}{(\sqrt{k_n \rho_n} + \sqrt{k_p \rho_p})^2}$$

n = Efficiency of thermopile

T_h = Hot junction temperature

T_c = Cold junction temperature

Z = Figure of merit

S_n = Seebeck coefficient of n-type material

S_p = Seebeck coefficient of p-type material

k_n = Thermal conductivity of n-type material

k_p = Thermal conductivity of p-type material

ρ_n = Resistivity of n-type material

ρ_p = Resistivity of p-type material

The purpose of the dotted curve is to provide a rough indication of the effective figure of merit of the thermoelectric ladder with braids, contacts, and heat leakage for the 1/2 inch diameter, 1/2 inch long thermoelements.

Couple Testing

Further tests were performed on the final couple design in an argon-hydrogen atmosphere with a temperature of 550°C on the hot side and 150°C at the cold side. The purposes of these tests were twofold: to determine if the life of the couple was satisfactory and to provide a means of evaluating couples for use in the generator. For these tests two modules were constructed and operated at the above specified temperatures. Module number 1(Figure 8) was continuously temperature cycled at a rate of five hours on and three hours off. Module number 2 (Figure 8) was cycled 15 times initially, eight hours on, 16 hours off and then allowed to operate continuously. Each module contained eight couples. At the completion of the generator construction, the modules operated a total of 1350 hours. Results are shown in Figure 8.

A sufficient number of couples were made so that by selection, only those having initial room temperature resistances less than 1.35 milliohms were used in the generator. Thus, with an average voltage output of 0.15V per couple and a hot resistance of 6 milliohms a nominal output of 1 watt or better would be expected from each couple. The measured efficiency of the couple was approximately 7 to 7.5 per cent at temperatures of 550°C at the hot junctions and 150°C at the cold junctions.

Predictions of System Performance

In order to predict generator performance, curves derived from couple efficiency test data, heat exchanger data and input heat flux measurements were sketched on one graphical design sheet (Figure 9). Families of curves were drawn of thermocouple heat flux versus cold strap temperatures with various hot side temperatures held constant. Superimposed was a family of curves representing heat exchanger temperature as a function of heat dissipation for various heat exchanger base plate areas. Power output curves as determined from the above conditions were shown with the number of couples as an additional variable. It was rather difficult to account on this graph for thermal drops resulting from hot and cold side interfaces and braid drops as shown in Figure 10, but in the final analysis, they all were accounted for.

With the understanding of basic heat transfer phenomena, it is readily seen that the intersection of the heat exchanger performance curve and the heat flux curve produced an operating point for specific hot and cold junction temperatures. All thermal losses including insulation losses, top and bottom plate losses etc. were corrected for.

Many operating points were available on this design curve. The choice was made in such a way as to produce a system of compromise between power output, efficiency and weight. It must be realized that all three above conditions cannot be optimized in one single system. The following were predictions of system performance before the construction of the generator.

1) Hot strap temperature (Avg) - 550°C

2) Cold strap temperature (Avg) - 170°C

3) Couple efficiency - 6.5 per cent

4) Overall generator efficiency - 5.5 per cent

5) Power output - 135 watts

6) Total power input - 2500 watts

Generator Heat Source

Thermoelectric generators require heat sources capable of transferring thermal energy to the thermoelements with high efficiency. The efficiency of heat transfer is a function of the heat source design, the heat transfer mechanisms, the heat flux density required for the thermoelements, internal temperature of the isotope and the temperature of the hot side of the generator. The following are the requirements to make the energy source compatible with the generator. These requirements are uniform duct or hot side temperatures for maximum utilization of the power conversion capabilities of the thermoelectric materials and high heat flux density for minimum generator size.

For the NAP-100 generator the heat exchanger, the thermocouple performance and the generator geometry determine to a large extent the performance requirements of the radioisotope fuel. The required characteristics of the heat source were analyzed to be as follows:

1) Packaged isotope size - 4" x 4" x 11"

2) Isotope container surface temperature - 600°C

3) Heat flux density approximately 14 watts per square inch of duct surface area

4) Heat required by the generator approximately 2500 watts or

8500 BTU/hr

5) Efficiency of heat transfer from the isotope to the generator core greater than 90 per cent, and

6) Minimum possible weight

A specific example of a fuel would be an alloy of $Curium_{242}$ containing 30% Nickel by weigh The radioisotope would have a half life of 162 days, a density of 9.02 grams/cc, and a power density of 34.9 watts/cc. This is an alpha emitter with a decay rate of 27.2 curie/watt. The cost per curie is $4.00. Assuming that, at the end of 1000 hours of generator operation 2500 thermal watts will be required, and using the formula for the initial quantity of isotope required for time t,

$$W_o = W_t \, e^{\frac{0.693t}{T\,1/2}}$$

where

t = 1000 hours = 42 days

W_t = 2500 watts

T1/2= half life = 162 days

W_o = 2500 x $e^{0.18}$ = 3000 watts

Volume of Isotope = 3000/34.9 = 86 cc = 5.25 cu in

Weight of Isotope = 86 x 9.02 = 776 gms = 1.7 lbs

Cost of Isotope = 3000 x 27.2 x 4.00 = $326,400

A rectangular fuel slug, 3/4" square and 9" long would be utilized. This slug would have a surface temperature of 1140 degrees C. The slug would be encapsulated in 1/8" thick Mo, Ni, Cr steel. The temperature drop across the 1/8" plate would be negligible. The capsule would then be sealed in a 3" x 3" x 10" block of titanium. Calculating the temperature on the outer surface of the titanium block:

Thermal conductivity of Ti = 8.1 BTU/hr ft degrees F

Heat flux per sq. in of capsule surface = 448 BTU/hr

Average Ti thickness = 1 inch

Average delta T across Ti = 375 degrees C

Outer surface temperature of titanium block = 765 degrees C

The weight of titanium = 15 lbs.

The sides of the titanium block would be covered with 1/2" slabs of graphite. The graphite has a thermal conductivity of 40-50 BTU/hr ft degrees F. The average delta T across the graphite would be 100 to 125 degrees C. The outer surface of the graphite would range from 640 degrees C to 665 degrees C. The ends of the titanium block should be covered with 1/2" of alumina (92-99% Al_2O_3 by wt.) This material has a thermal conductivity of 1 to 2 BTU/hr ft degrees F. The average delta T across the alumina would be 420 degrees C. The outer surface temperature of the Al_2O_3 would be 245 degrees C. The weight of the graphite and alumina would equal 7.2 lbs.

The total weight of the power unit would be 24 pounds. The size would be 4" x 4" x 11". The inch of titanium metal and the 1/2 inch of graphite would be an effective alpha radiation shield. Since the incorporation of the nuclear heat source was not part of the contract, a simulating electrical heat source was delivered with the generator which met all the above requirements.

GENERATOR ASSEMBLY DETAILS

The basic arrangement of the generator consists of a hot side (core) and a cold side (heat exchanger) with thermoelectric units between the two. The core is a rectangular structure made of stainless steel clad copper with flanges welded at the top and bottom. Two metallic plates are welded to the top and bottom flanges and serve as the supporting structure between the hot and cold sides as well as the hermetic seal at top and bottom of the generator. On the cold side, the thin plate is welded to a frame as shown in Figure 11. The frame is made of stainless steel and its window-like arrangement provides mounting surfaces for the aluminum heat exchangers on all four sides. A silicone rubber gasket between the frame and the heat exchangers seals the interior of the generator from the outside atmosphere. A refractory enamel coating similar to National Bureau of Standards A-418 is sprayed on the hot core and baked. The face of the core is then covered with a layer of mica paper; the hot-side matrix, which is made of mica board, is placed on top of the mica paper. This matrix, which has slots machined in it at regular intervals, is used to provide proper spacing for the thermocouples on the hot side, while the glass coating and mica paper provide electrical insulation between the elements and the generator parts. The couple hot straps, which are metallurgically bonded to the semiconductor materials at the pilot plant, are inserted into the matrix slots. Springs are then placed around the copper braid, which is bonded in the same manner to the semiconductor materials as the hot straps.

Following the above operations, the cold side soldering fixture (Figure 12) is assembled. This fixture is an aluminum block which has milled slots on one face that serve to align and space the cold side straps. These straps are inserted in the fixture slots with the tinned side up and held in the slots with a small amount of silicone grease. A soldering flux is applied to the tinned side of the straps and to the top of the copper braids. The fixture is then bolted on the generator frame in the same manner as the heat exchanger, slightly compressing the springs and braids and insuring contact between the top of the copper braids and the tinned part of the cold side straps. The generator and the soldering fixture are placed on a hot plate and the soldering is accomplished at a temperature of 280°C. The unit is cooled and the fixture removed. The sweat joints thus formed between the copper braids and the cold side straps are tested electrically to assure that good contact has been obtained and that couples have not been damaged. Assembly of thermoelectric elements is completed by soldering on two electrical leads which extend through the heat exchanger. Following this operation, a cold side matrix is placed around the cold straps to prevent contact between them.

The anodized heat exchanger is prepared by coating the base with thermal conducting paste. A layer of mica paper is placed on this surface to provide further electrical insulation between the cold straps and heat exchanger. More thermal paste is in turn spread on the mica paper. After a gasket is placed on the generator frame, the heat exchanger is bolted down. This compresses the copper braid and spring assembly a distance of 1/16", thus realizing a compressive force of five pounds on each leg of the thermoelectric elements. Before the last heat exchanger is installed on the generator, thermal insulation is poured in between the thermoelectric elements.

After the installation of the heat exchangers, feedthroughs are inserted around the electrical leads and then sealed. The leads are connected so as to provide a series arrangement between the four sides, with two of the feedthroughs providing the output leads. A base is then attached to the bottom of the generator. The complete generator assembly is shown in Figure 1.

GENERATOR TESTS AND PERFORMANCE

During the fabrication of the generator, continual checks were made of the room temperature resistance of the couples to make certain that no damage was done when the cold straps were soldered to the braids or when springs and braids were compressed and the heat exchangers applied. No significant change was apparent in the resistances during the various fabricating procedures.

After assembly, the generator core was brought up to a temperature of 450°C and the thermal distribution on the core was checked. During this time, the generator was pumped out with a vacuum pump to remove the water vapor and other contaminants, after which the generator was charged with an inert gas. A series of performance tests was run on the generator and it was found that the unit produced the required 100 watts at a hot side temperature of 475°C. The temperature was then brought up to 550°C; output at this condition was 131 watts at 10 volts. Results of the above tests are shown in Figure 13. Typical test results are given in Table II.

TABLE II - PERFORMANCE DATA ON NAP-100 GENERATOR

Internal Resistance (room temp.)	236 milliohms
Internal Resistance (oper. temp.)	834 milliohms
V (open circuit voltage)	20.9 volts
Power Output (at max. power transfer)	131 watts
T_h Hot Junction Temp. (avg. of hot core)	554°C
T_c Cold Strap Temp. (avg. of cold side)	171°C
Elec. Power Output/Total Power Input measured	5.16%
Elec. Power Output/Thermal Flux Through Generator (estimated)	6.20%
Total Weight	38 lbs

Following the above tests, an additional series of tests was performed to observe the behavior of the generator when external load conditions were changed. During these tests, the generator input heat was held constant while the external load was incrementally varied. The changes in hot and cold side temperatures were recorded as well as the corresponding generator power output. The results are shown in Figures 14 and 15. The generator was cycled eight times, the total testing time was 29 hours.

Following the delivery of the NAP-100 generator to Air Force Special Weapons Center, a series of tests was performed by the Test Directorate on the unit. The first of these was an ambient temperature performance test, in which generator performance was checked under room temperature conditions. Results of this test are shown in Figure 16. The generator was then placed in a climatic chamber where its performance was checked under surrounding temperature conditions of 0°C and -45°C. Under these conditions, it was noticed that the hot strap thermocouple readings were greatly spread in value, producing a variation of temperature of 100°C. This could be explained by the temperature change along the temperature measuring thermocouples as they were fed through from the climatic chamber to the recording instruments. The possibility also arises that the thermocouples might have separated from the hot straps. Results of the above tests are shown in Figures 17 and 18.

Impedance matching tests as well as internal resistance checks at ambient temperature for various hot strap temperatures were also performed at AFSWC confirming conditions of maximum power transfer. Figure 19 and Table III show the results of these tests. In addition, the four sides of the generator were connected in parallel. The unit was operated at hot strap temperatures of 300°C and 500°C. Currents of 20 to 35 amperes and voltages of 1.0 to 2.3 volts were attained at AFSWC. The internal impedences of the four sides were within 4% of each other. Such a difference produced a negligible power loss under maximum power transfer condition and parallel operation. At this point, the unit operated for approximately 165 hours.

Finally, the generator was put on life test. For 335 hours, the generator output averaged 80 watts at 515°C. At the end of that time, failure of two sides terminated the test. Failure was identified by Test Directorate Engineers as a separation of a number of hot side contacts between the hot strap and the thermoelectric material, resulting in an open circuit. No other damage was reported.

CONCLUSIONS

The attempt at predicting generator performance as explained previously was considerably more successful than expected. We must realize that test data was taken of generator components as they performed separately and under idealistic conditions. In order to integrate this data into a generator system, many assumptions had to be made. These assumptions were based on results obtained from previous generator units and modules and were corrected for this particular case. The high accuracy of the prediction as substantiated by the initial generator performance will enable the designer to efficiently expedite future generator designs. It will also provide a tool for design comparison on the basis of maximum efficiency, maximum power output and minimum weight.

The expected lifetime of one year's unattended operation was however, not attained. Following the initial 30 hours of preliminary testing at the Westinghouse New Products Research Laboratories approximately 500 hours of operation was performed at the Air Force Special Weapons Center. Operation included over fifty cyclic operations, environmental temperature changes of over 50°C, bank connection changes, impedence matching tests and life test. The specified power output of 100 watts at 12 volts was achieved at a hot strap temperature of 550°C and ambient surroundings. The over-all efficiency at the above conditions was 5.2%.

Part 1 and Part 2 of the contract called for generator units with the same power output.[2] The main difference being in the type of heat source to be utilized in each. The TAP-100 generator which completed part one of the contract utilized fossil fuel burning.[3,4] Upon its delivery, it was pointed out that improvements in performance would be accomplished in the design of the NAP-100 generator. Since the designs of the generators are similar comparisons of the performances of each illustrates the rapid improvement in the state of the art.

		TAP-100	NAP-100
1)	Number of Thermoelectric Couples	140	140
2)	Internal Resistance (cold)	.34 ohms	.24 ohms
3)	Internal Resistance (Operating Temp.)	.96 ohms	.83 ohms
4)	Open Circuit Voltage	19.7 V	20.9 V
5)	Power Output (max. power transfer)	102.5 W	131 W
6)	Core Temperature (average)	582°C	554°C
7)	Heat Exchanger Temperature (average)	154°C	171°C
8)	Electrical Power Output/Thermal Flux through Generator	3.7%	6.2%
9)	Total Weight	47 lbs.	38 lbs.

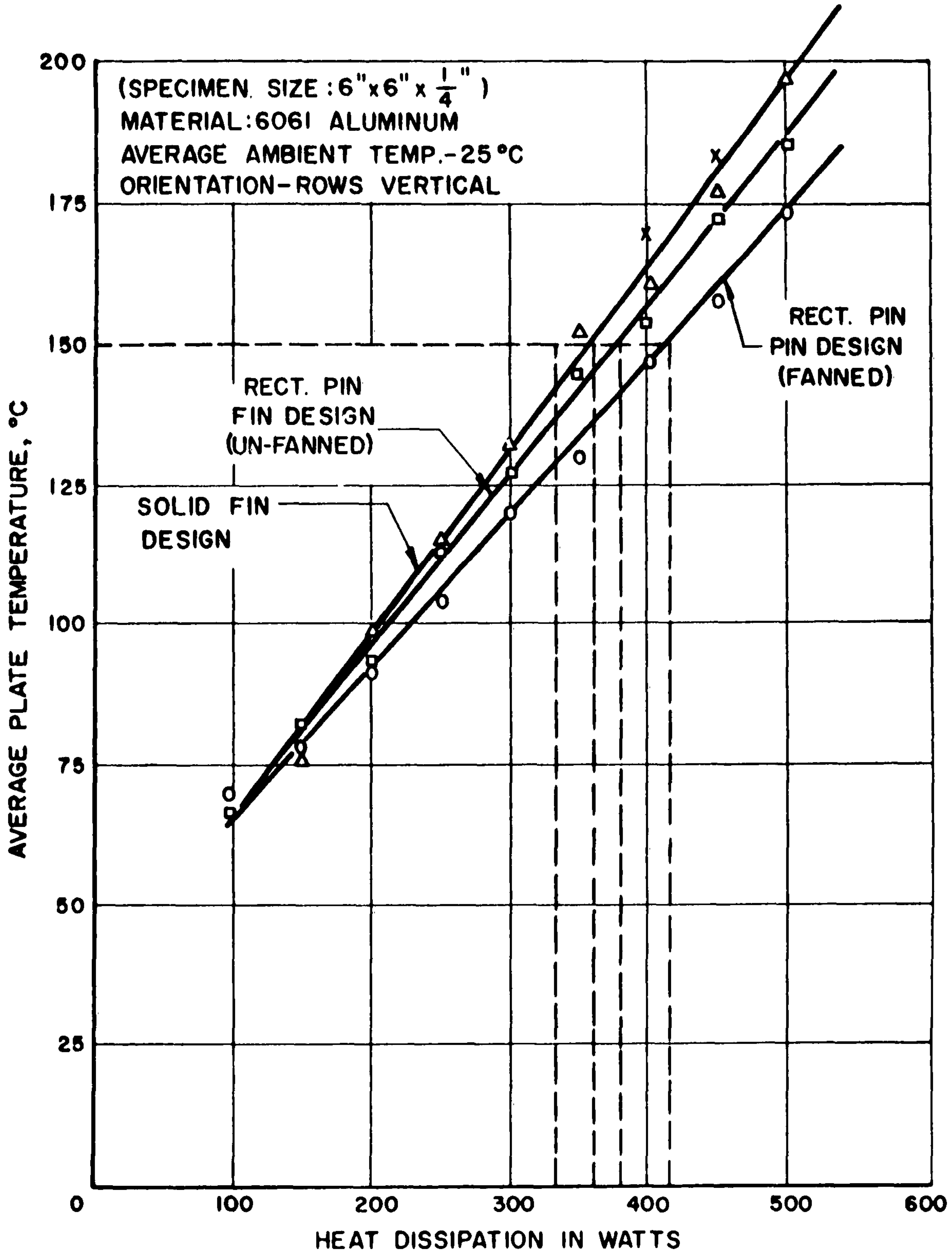
TABLE III

INTERNAL RESISTANCE AT AMBIENT TEMPERATURE

Hot Strap 200°C			Hot Strap 300°C		
R_{Load} V_L/I_L	R_{in} $(V_0-V_L)\ I_L$	Δ Hot Strap °C	R_{Load} V_L/I_L	R_{in} $(V_0-V_L)I_L$	Δ Hot Strap °C
1.74	.505	+8	1.90	.674	+6
1.52	.481	+7	1.52	.658	+6
1.19	.499	+7	1.31	.656	+6
1.32	.513	+6	1.18	.655	+6
1.09	.503	+6	1.04	.640	+5
.947	.503	+6	.876	.641 max.	+5
.752	.502	+4	.8	.653	+5
.60	.489 max.	+3	.095	.636	+8 +3
.499	.498	+3	.789	.643	+3
.389	.500	+3	.678	.640	+2

Hot Strap 500°C			Hot Strap 550°C		
1.79	.88	+7	2.2	.884	+4
1.585	.867	+5	1.88	.901	+3
1.405	.877	+4	1.76	.912	+2
1.2	.875	+3	1.50	.882	+0
1.01	.875 max.	+3	1.32	.882	-2
.856	.874	-1	1.215	.879	-3
.958	.862	+2	.972	.88 max.	-5
.968	.87	+4	.829	.88	-7
.827	.862	-2	1.082	.878	-10
.682	.945	-3	.682	.89	-15
.459	.940	-5	.455	.89	-17
.238	.86	-9			
1.04	.864	-2			

Fig. 1



FIN AND PIN SURFACES AS HEAT EXCHANGERS

FIG. 2

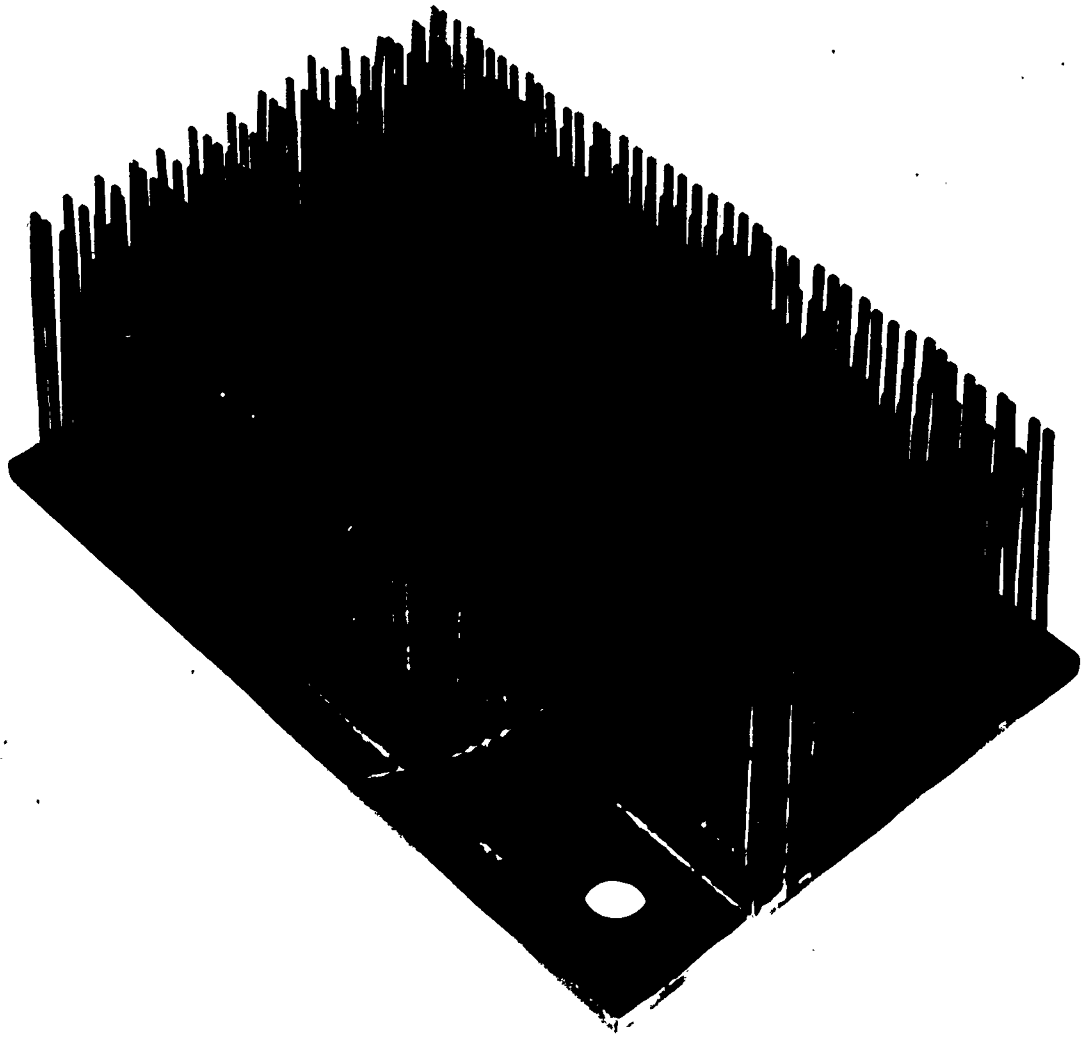


Fig. 3

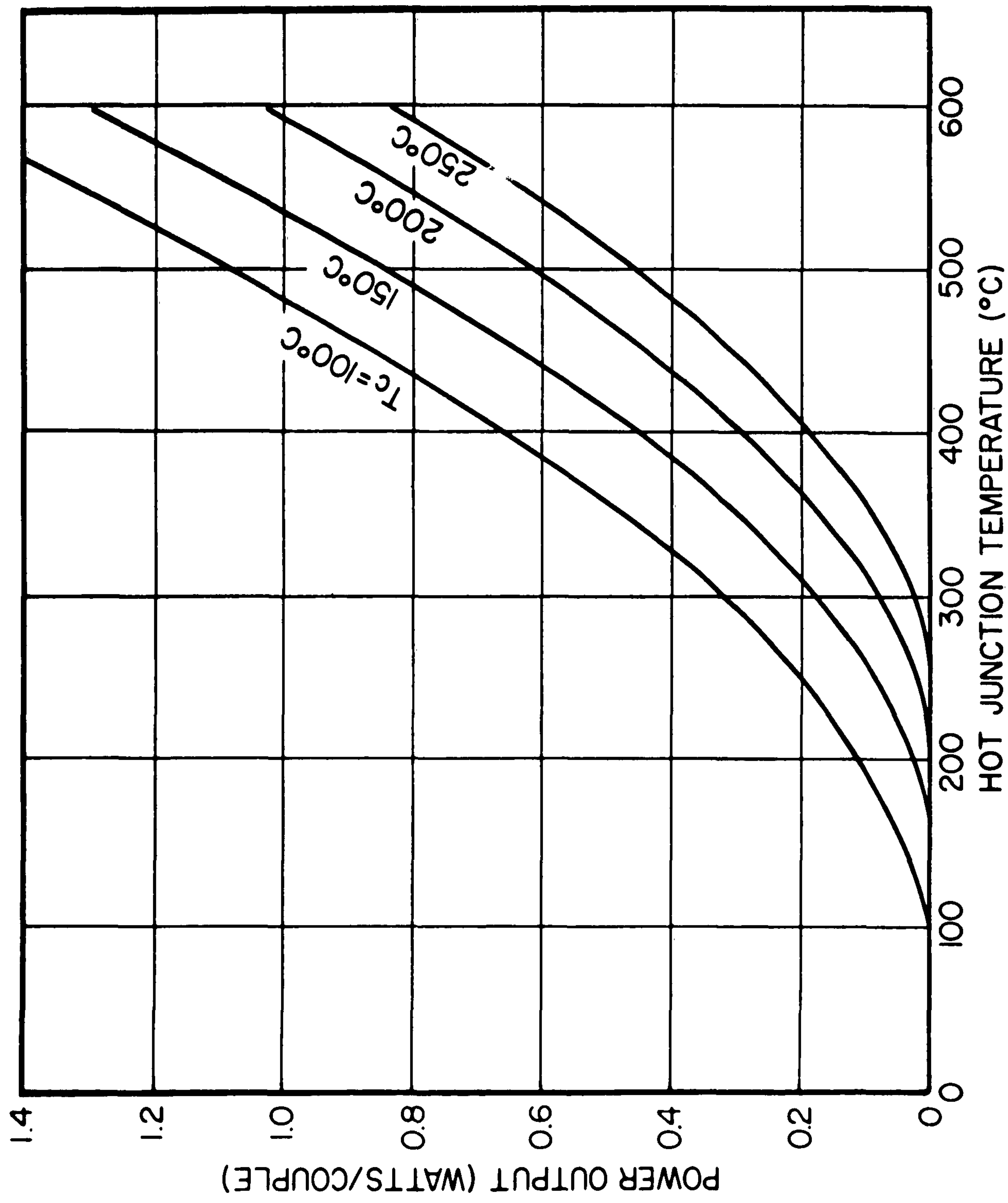
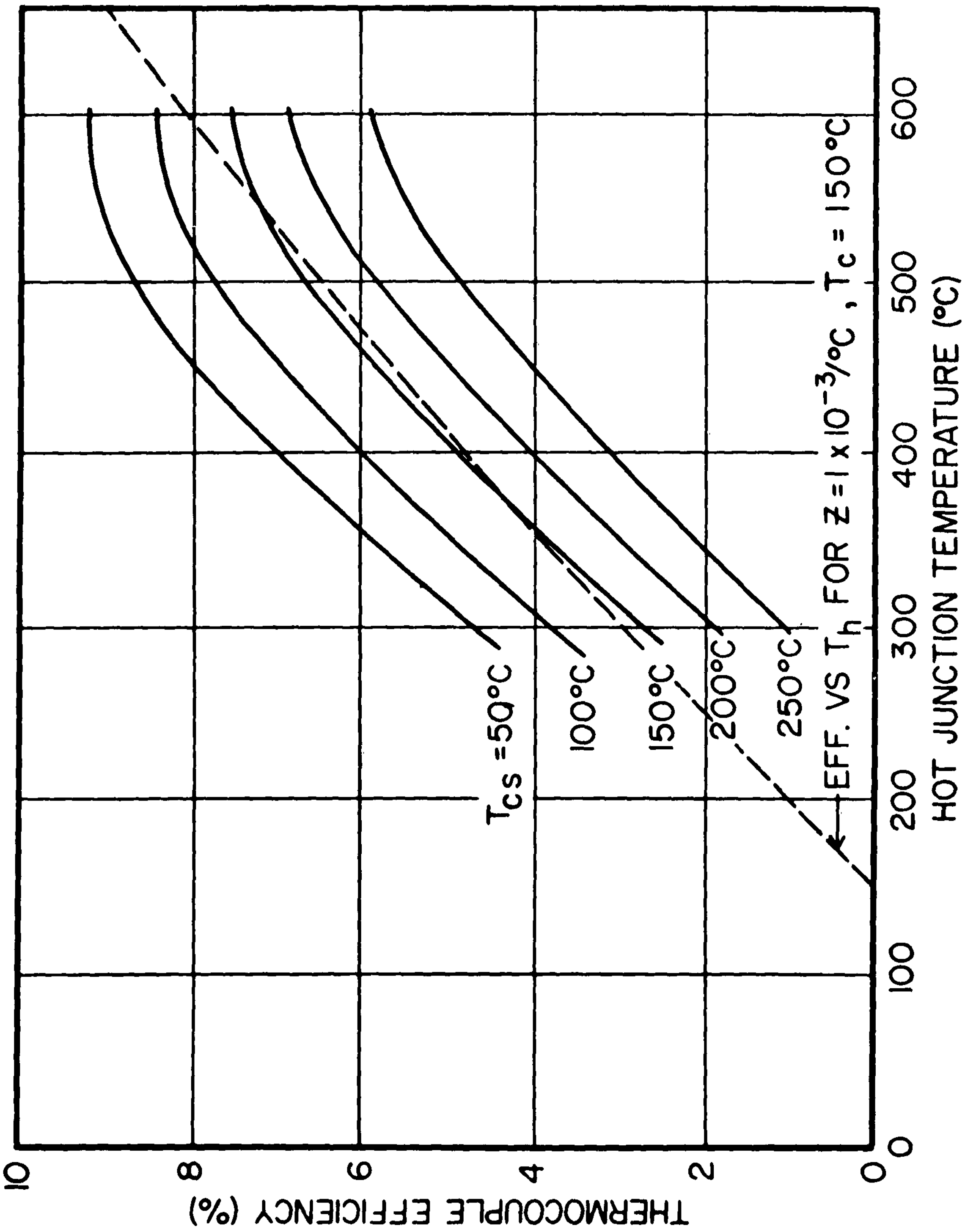

POWER OUTPUT (WATTS/COUPLE)
HOT JUNCTION TEMPERATURE (°C)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
100
200
300
400
500
600
Tc=100°C
150°C
200°C
250°C

FIG. 4



THERMOCOUPLE EFFICIENCY (%)
HOT JUNCTION TEMPERATURE (°C)
0
2
4
6
8
10
100
200
300
400
500
600
T_{CS} =50°C
100°C
150°C
200°C
250°C
EFF. VS T_h FOR $Z = 1 \times 10^{-3}/°C$, T_c = 150°C

FIG. 5

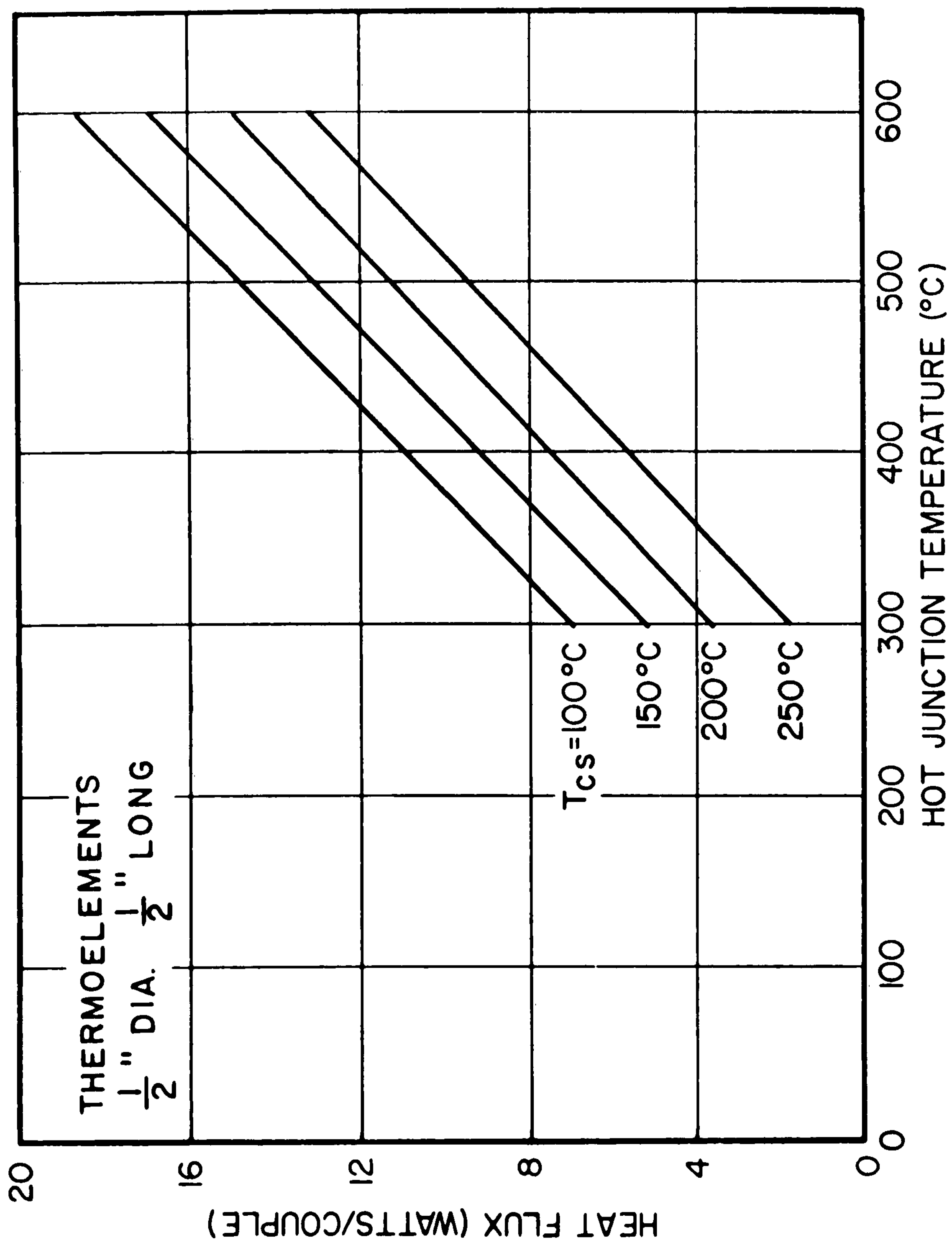

THERMOELEMENTS
1/2" DIA. 1/2" LONG
HEAT FLUX (WATTS/COUPLE)
HOT JUNCTION TEMPERATURE (°C)
Tcs=100°C
150°C
200°C
250°C
0
4
8
12
16
20
0
100
200
300
400
500
600

FIG. 6

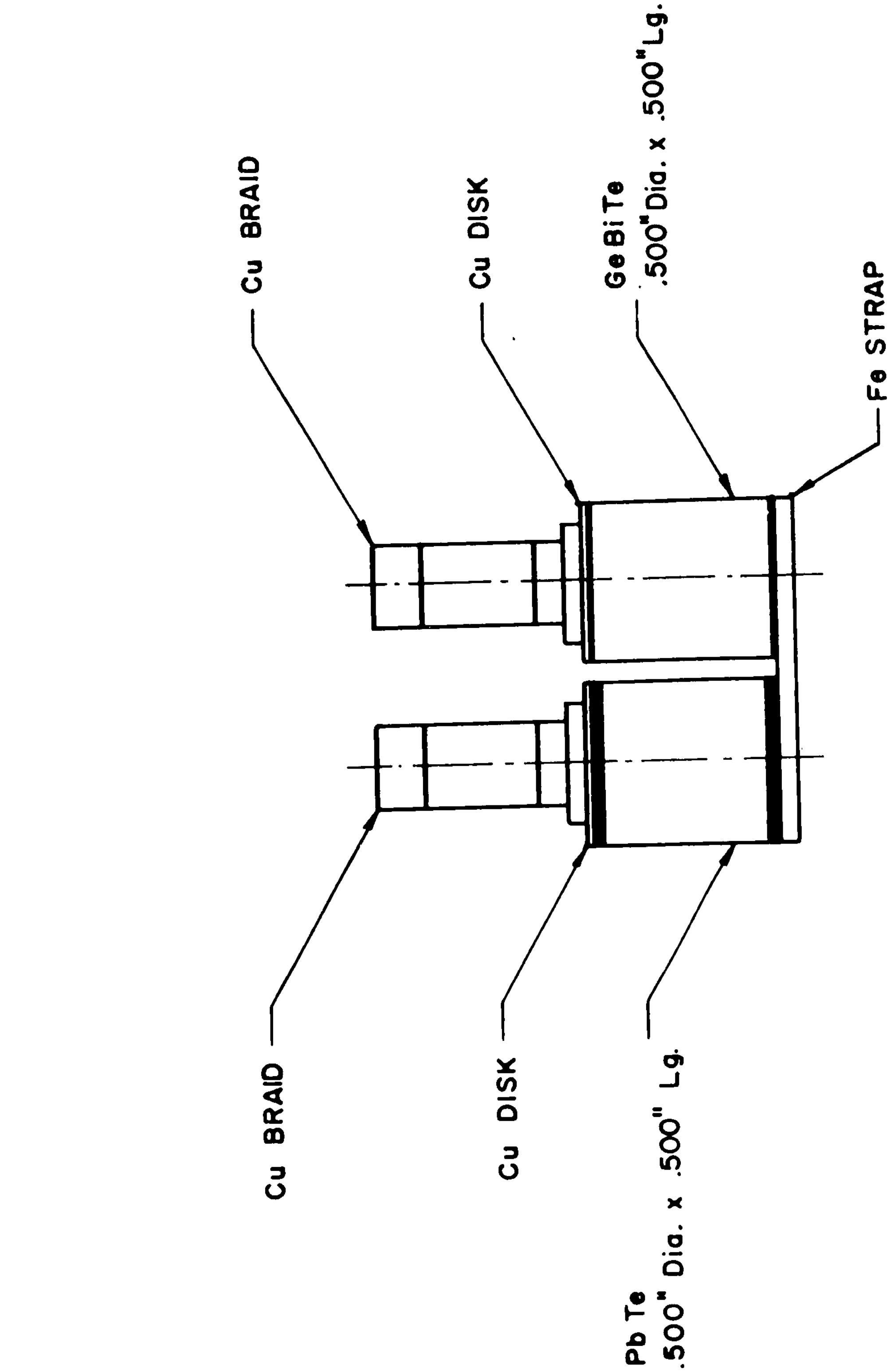
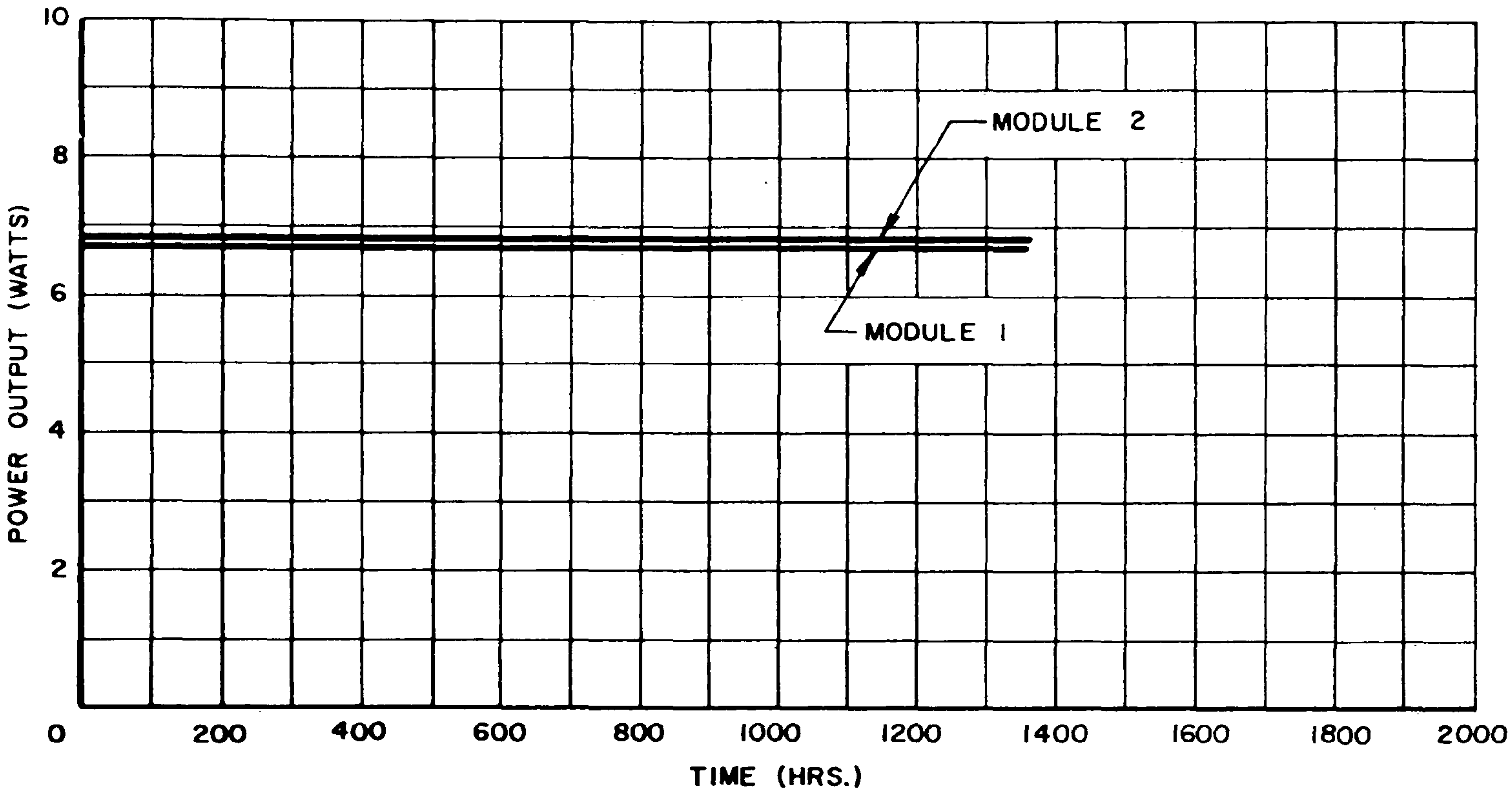

Cu BRAID
Cu DISK
Ge Bi Te
.500"Dia. x .500"Lg.
Fe STRAP
Cu BRAID
Cu DISK
Pb Te
.500" Dia. x .500" Lg.

FIG. 7



MODULE #1 - 8 x TAP-100F COUPLES

1.) <u>COLD SIDE INSUL.</u> - MICA PAPER

2.) <u>HOT SIDE INSUL.</u> - GLASS & PHLOGOPITE

3.) <u>AV. HOT STRAP TEM.</u> - 550°C - 60% TIME, 530°C 40% TIME.

MODULE #2 - 8 x TAP-100F COUPLES

FILM ADHESIVE

GLASS, 1/2 GOLD, 1/2 AL, PHLOGOPITE,

550°C - 50% 530° - 50%

FIG. 8

NAP-100 LIFE TEST MODULES

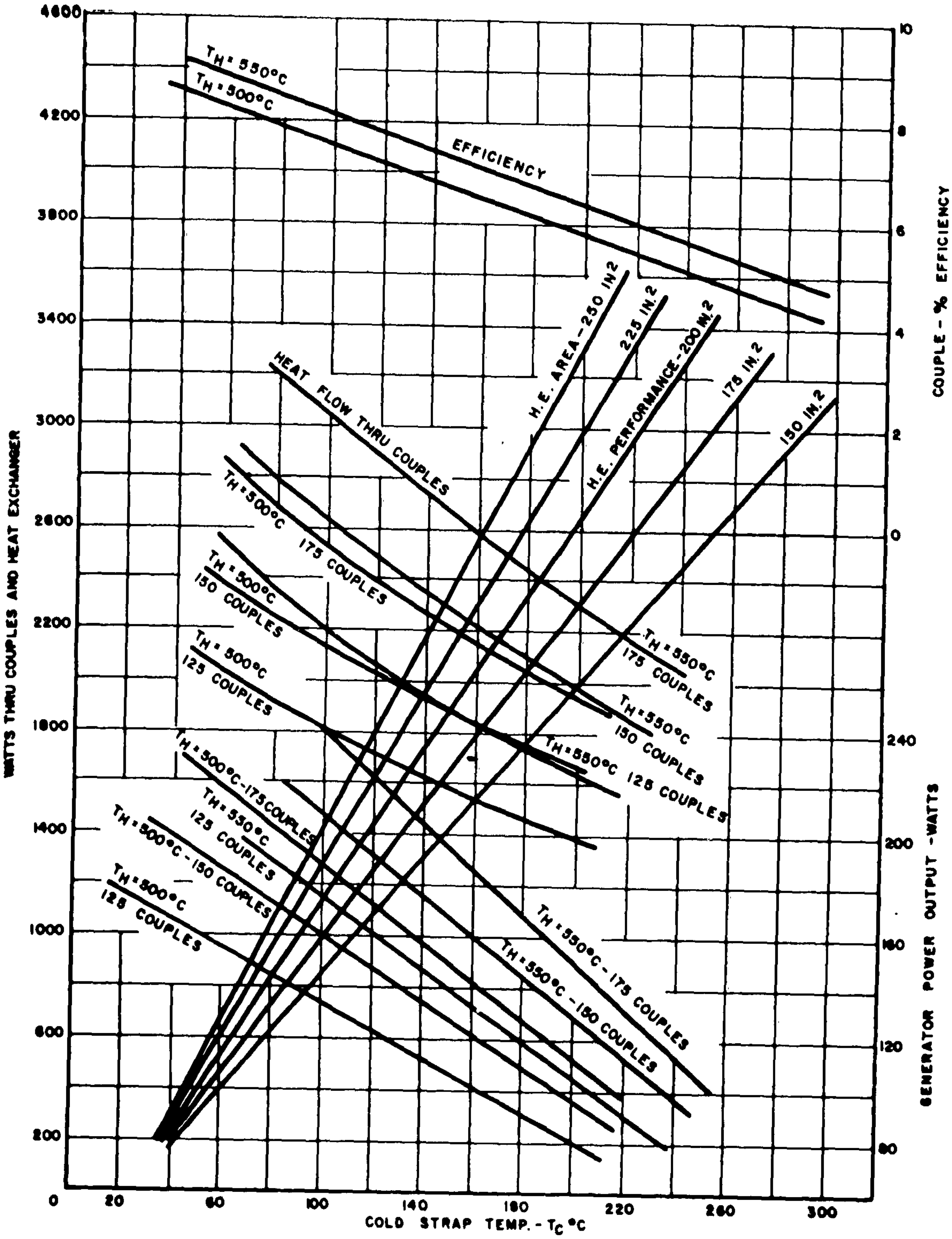


FIG. 9

DESIGN PARAMETERS

FOR

FREE CONVECTION COOLED T/E GENERATOR

TAP-100F T/E COUPLE

3 1/4 IN. PIN FIN H. EXCHANGER

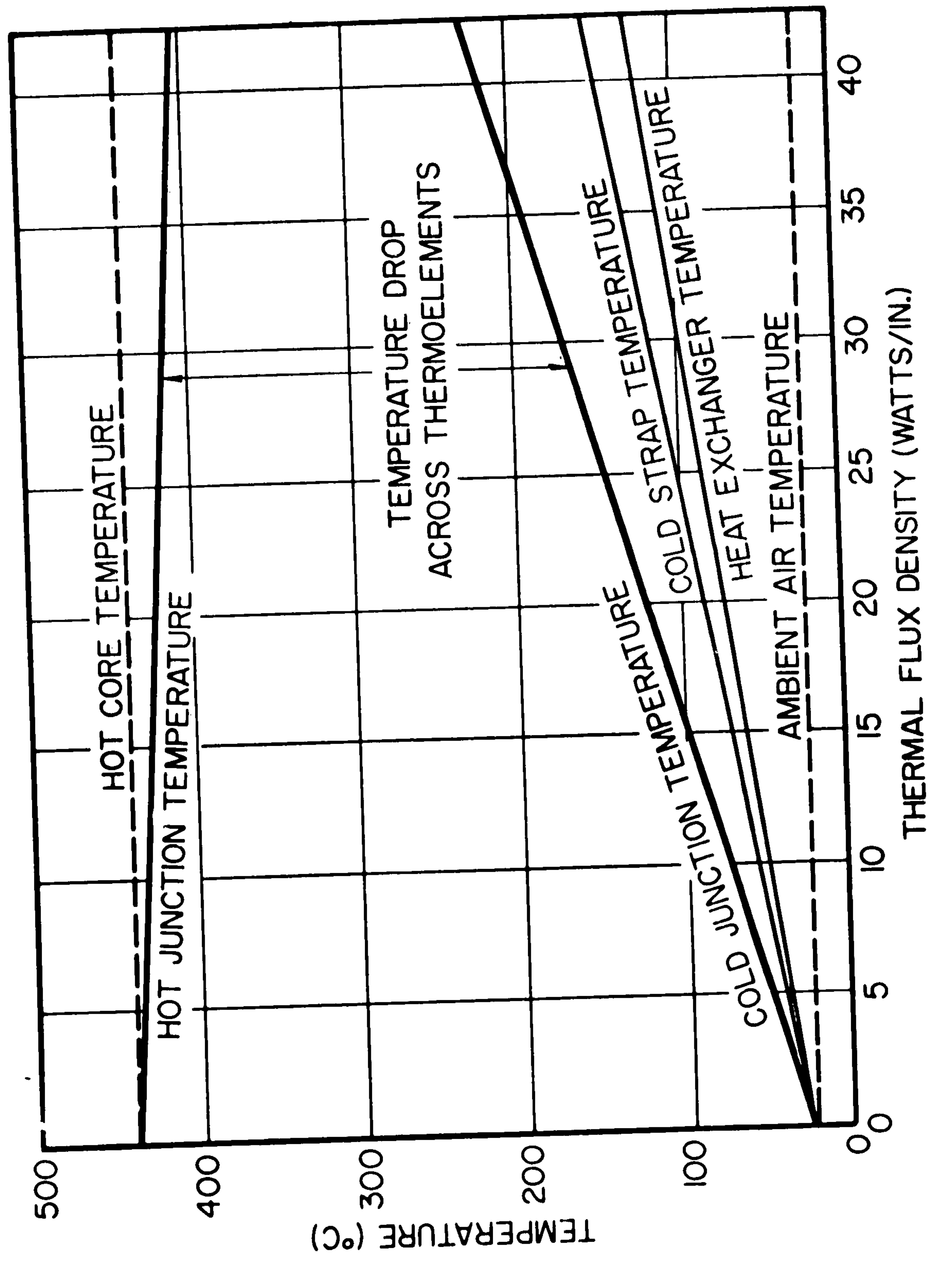

HOT CORE TEMPERATURE
HOT JUNCTION TEMPERATURE
TEMPERATURE DROP
ACROSS THERMOELEMENTS
COLD JUNCTION TEMPERATURE
COLD STRAP TEMPERATURE
HEAT EXCHANGER TEMPERATURE
AMBIENT AIR TEMPERATURE
TEMPERATURE (°C)
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
THERMAL FLUX DENSITY (WATTS/IN.)

FIG. 10

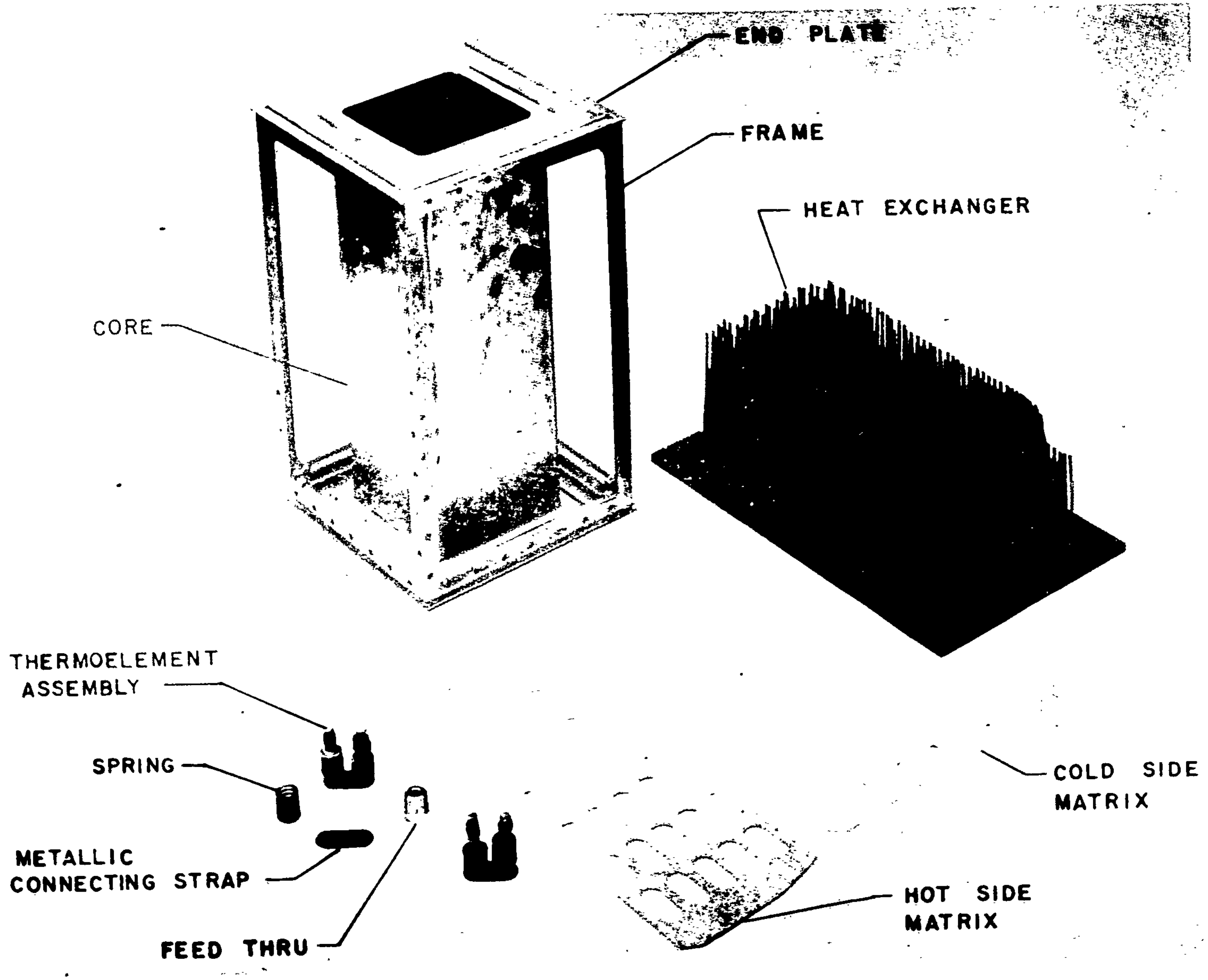
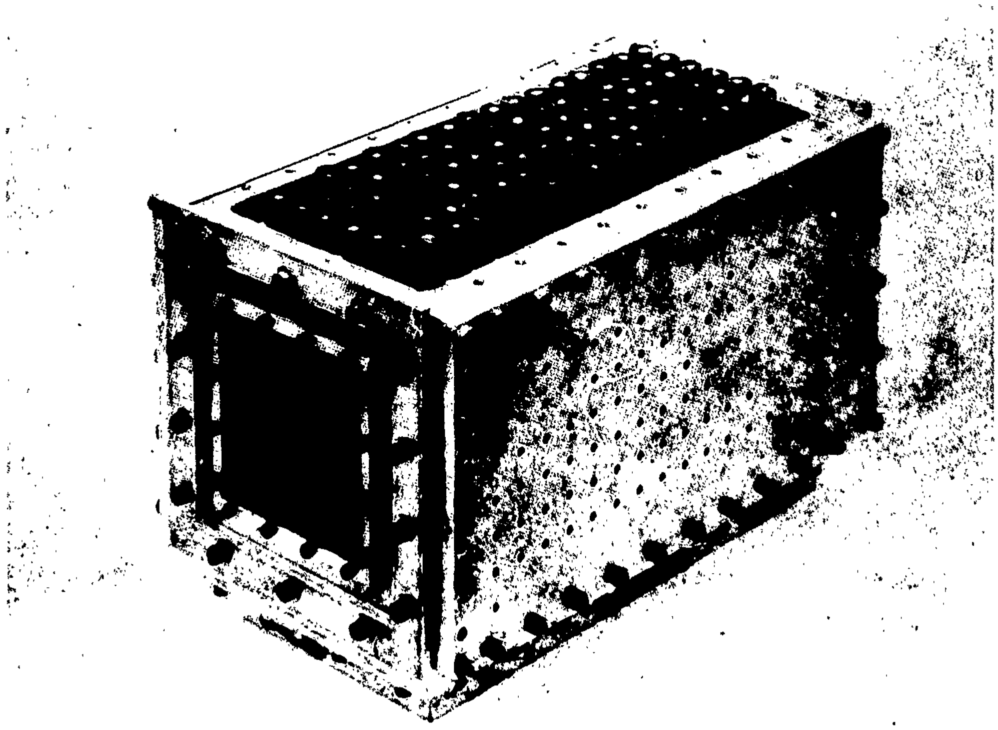

END PLATE
FRAME
HEAT EXCHANGER
CORE
THERMOELEMENT ASSEMBLY
SPRING
METALLIC CONNECTING STRAP
FEED THRU
COLD SIDE MATRIX
HOT SIDE MATRIX

Fig. 11



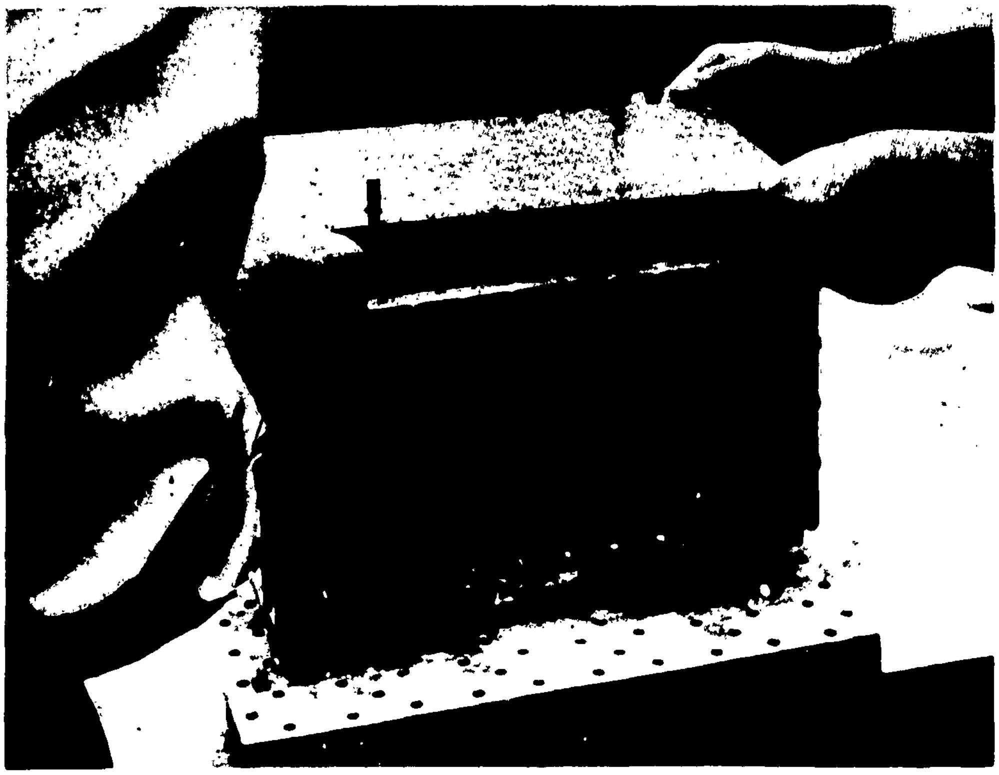


Fig. 12

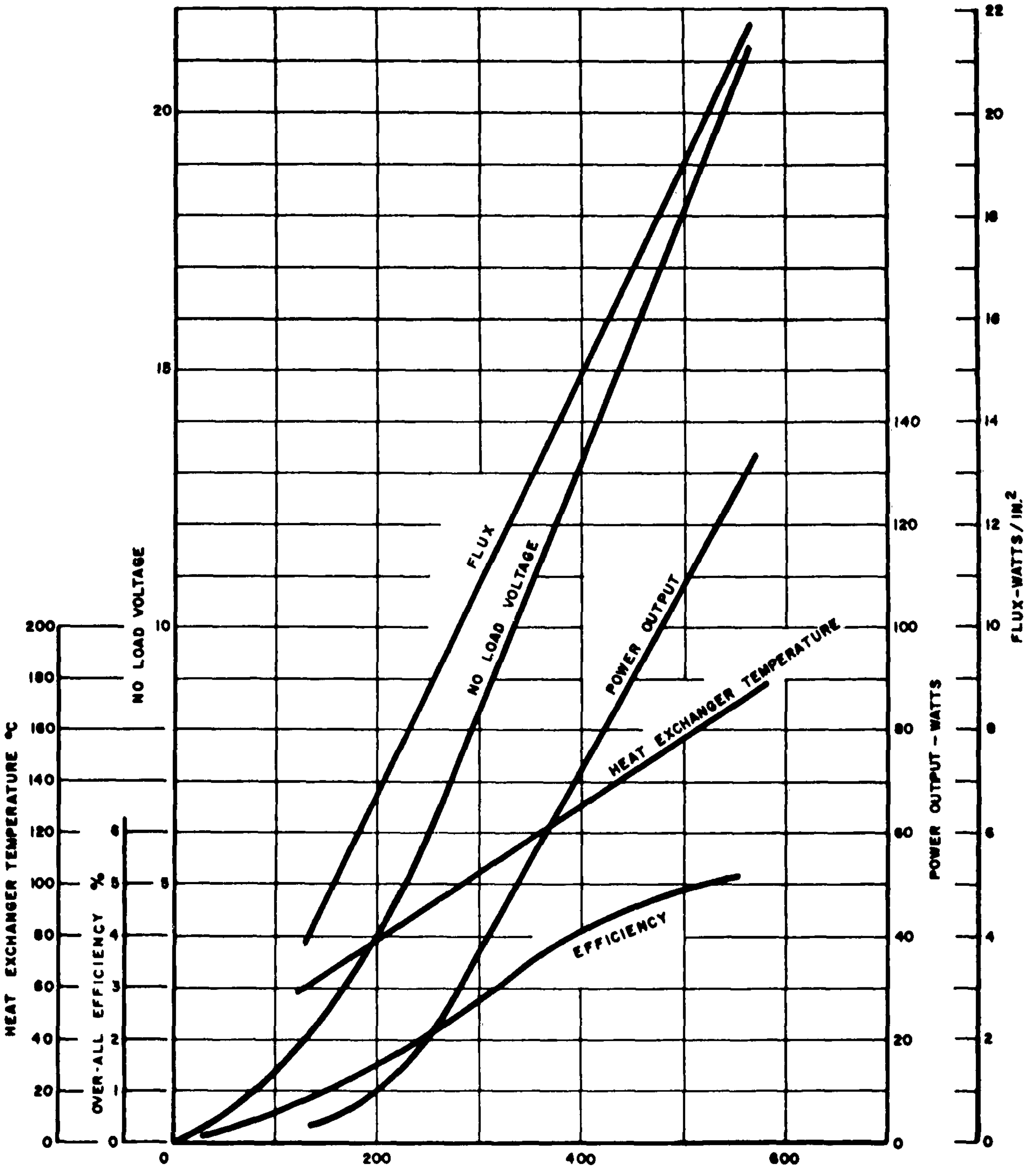


FIG. 13

NAP-100 T/E GENERATOR
HOT STRAP TEMPERATURE
V.S.
EFFICIENCY
POWER OUTPUT
NO LOAD VOLTAGE
FLUX

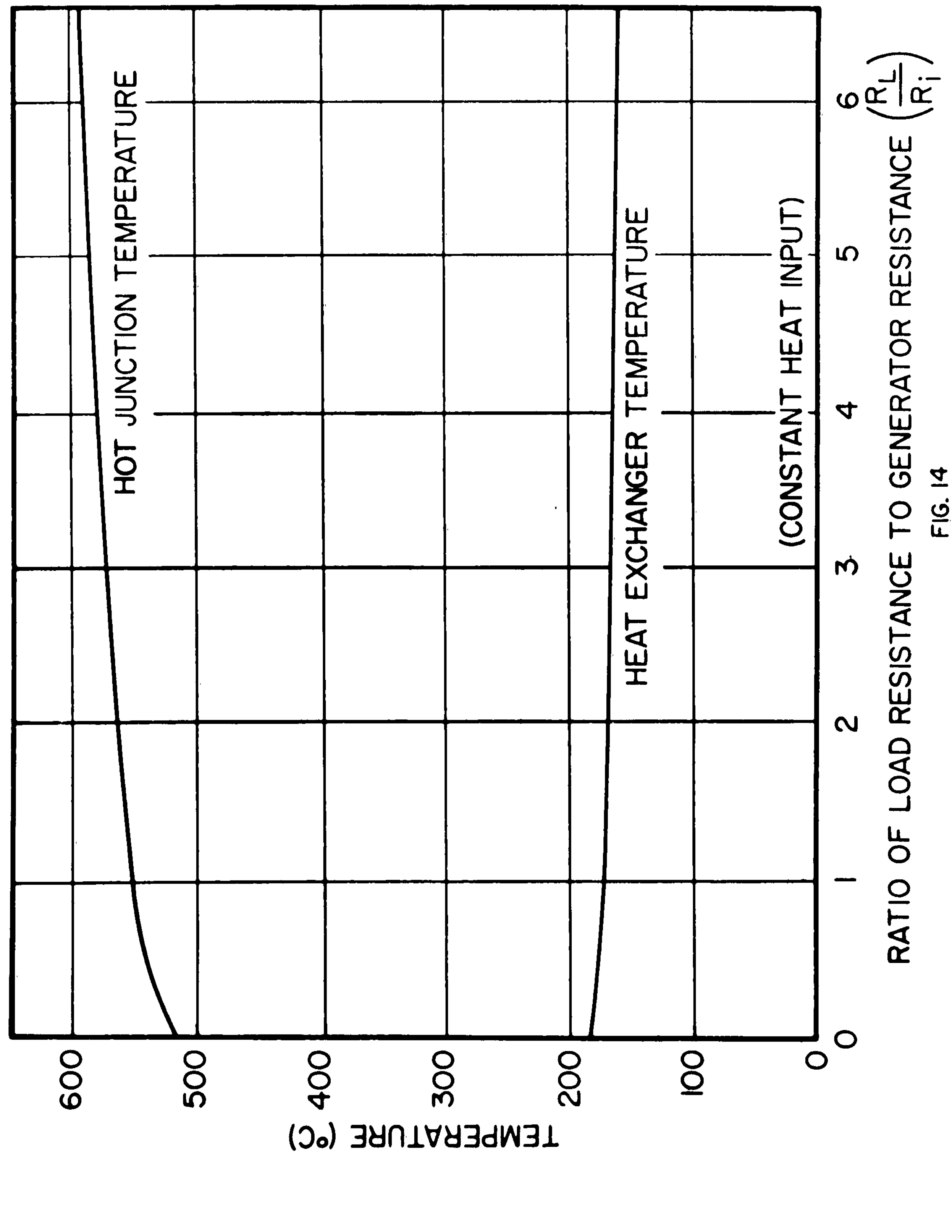

HOT JUNCTION TEMPERATURE
HEAT EXCHANGER TEMPERATURE
(CONSTANT HEAT INPUT)
TEMPERATURE (°C)
0
100
200
300
400
500
600
0
1
2
3
4
5
6
RATIO OF LOAD RESISTANCE TO GENERATOR RESISTANCE $\left(\frac{R_L}{R_i}\right)$

FIG. 14

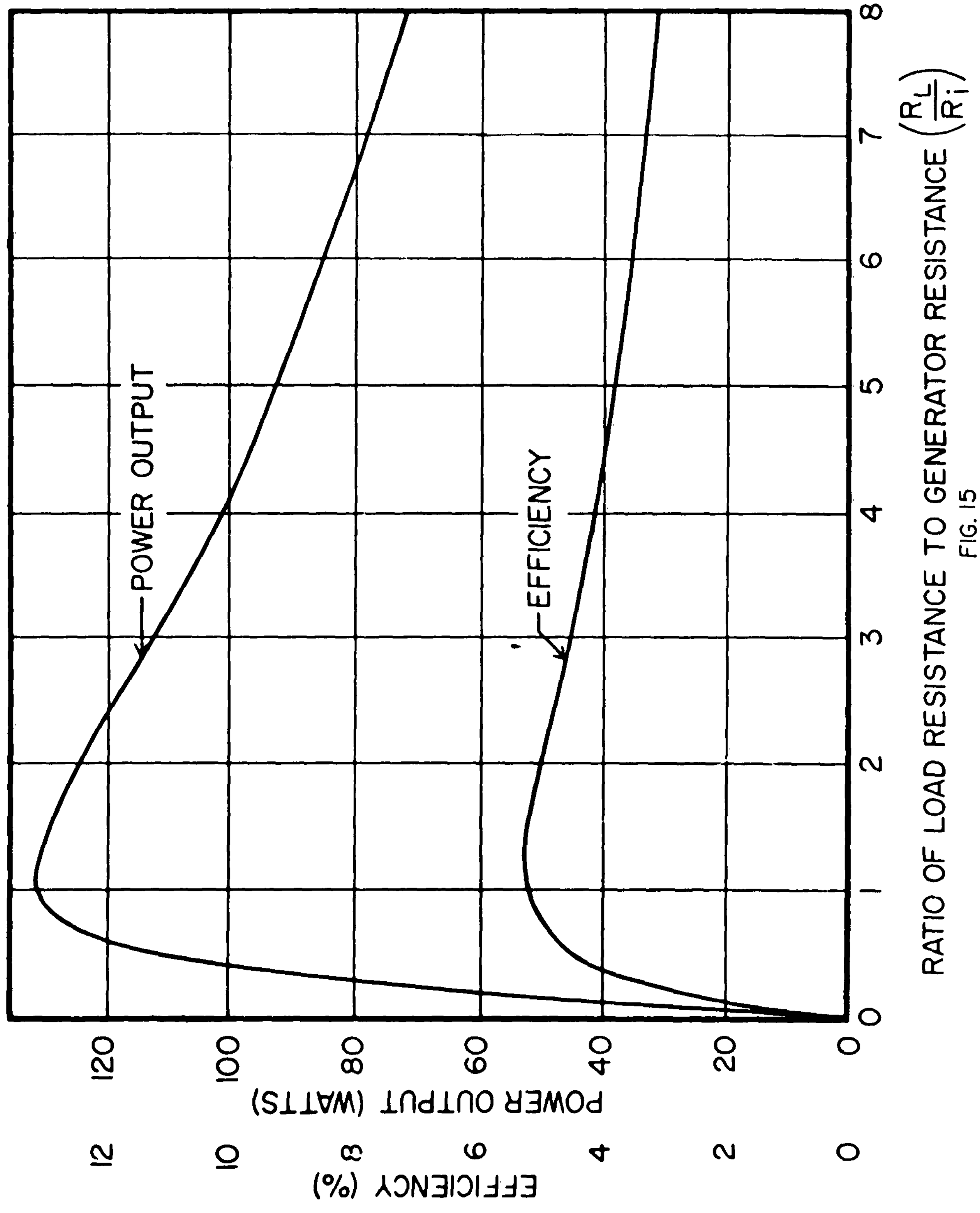
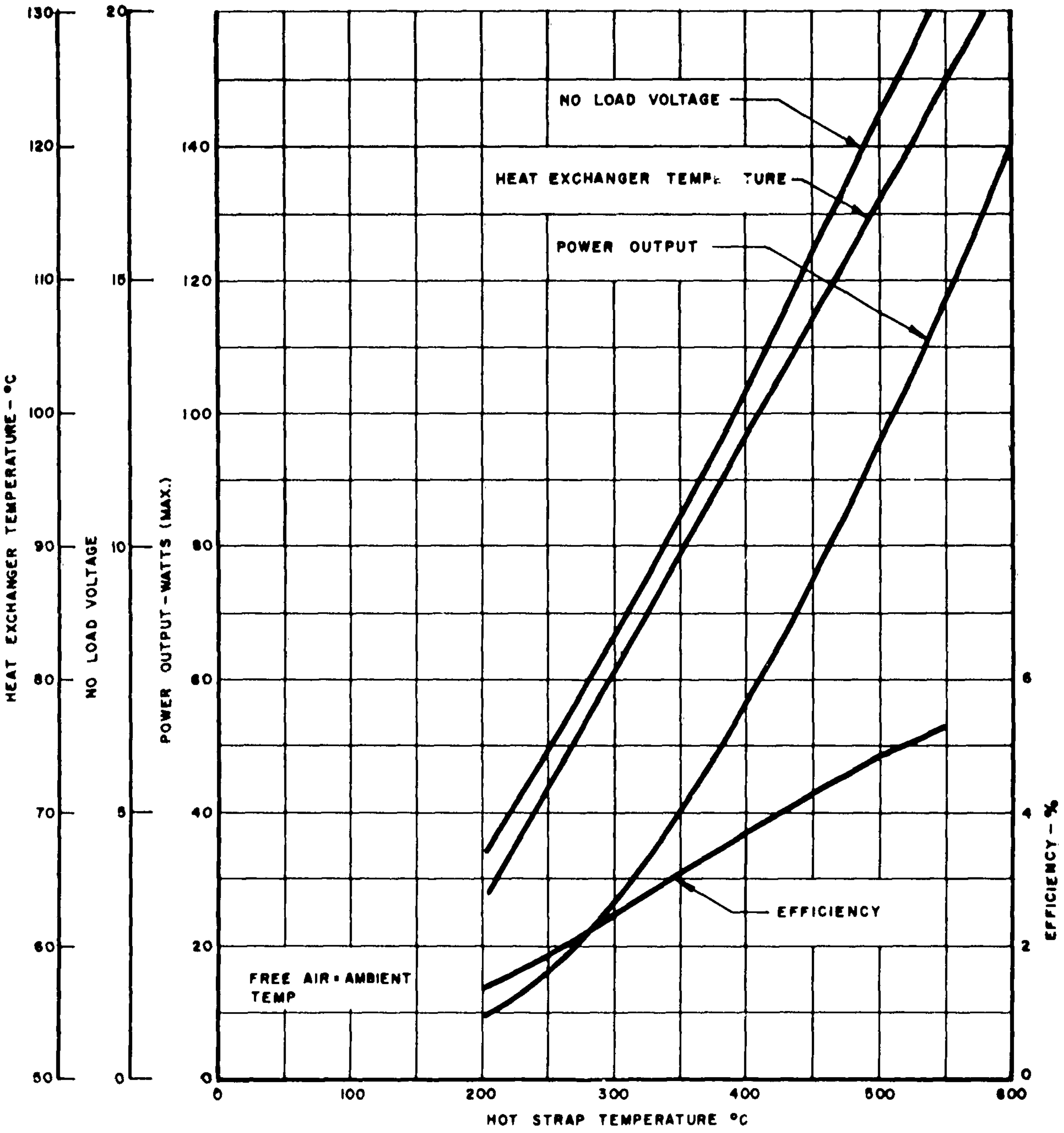

POWER OUTPUT
EFFICIENCY
POWER OUTPUT (WATTS)
EFFICIENCY (%)
0
20
40
60
80
100
120
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
RATIO OF LOAD RESISTANCE TO GENERATOR RESISTANCE $\left(\frac{R_L}{R_i}\right)$

FIG. 15



HEAT EXCHANGER TEMPERATURE - °C
NO LOAD VOLTAGE
POWER OUTPUT-WATTS (MAX.)
EFFICIENCY - %
HOT STRAP TEMPERATURE °C
NO LOAD VOLTAGE
HEAT EXCHANGER TEMP TURE
POWER OUTPUT
EFFICIENCY
FREE AIR = AMBIENT TEMP

FIG. 16

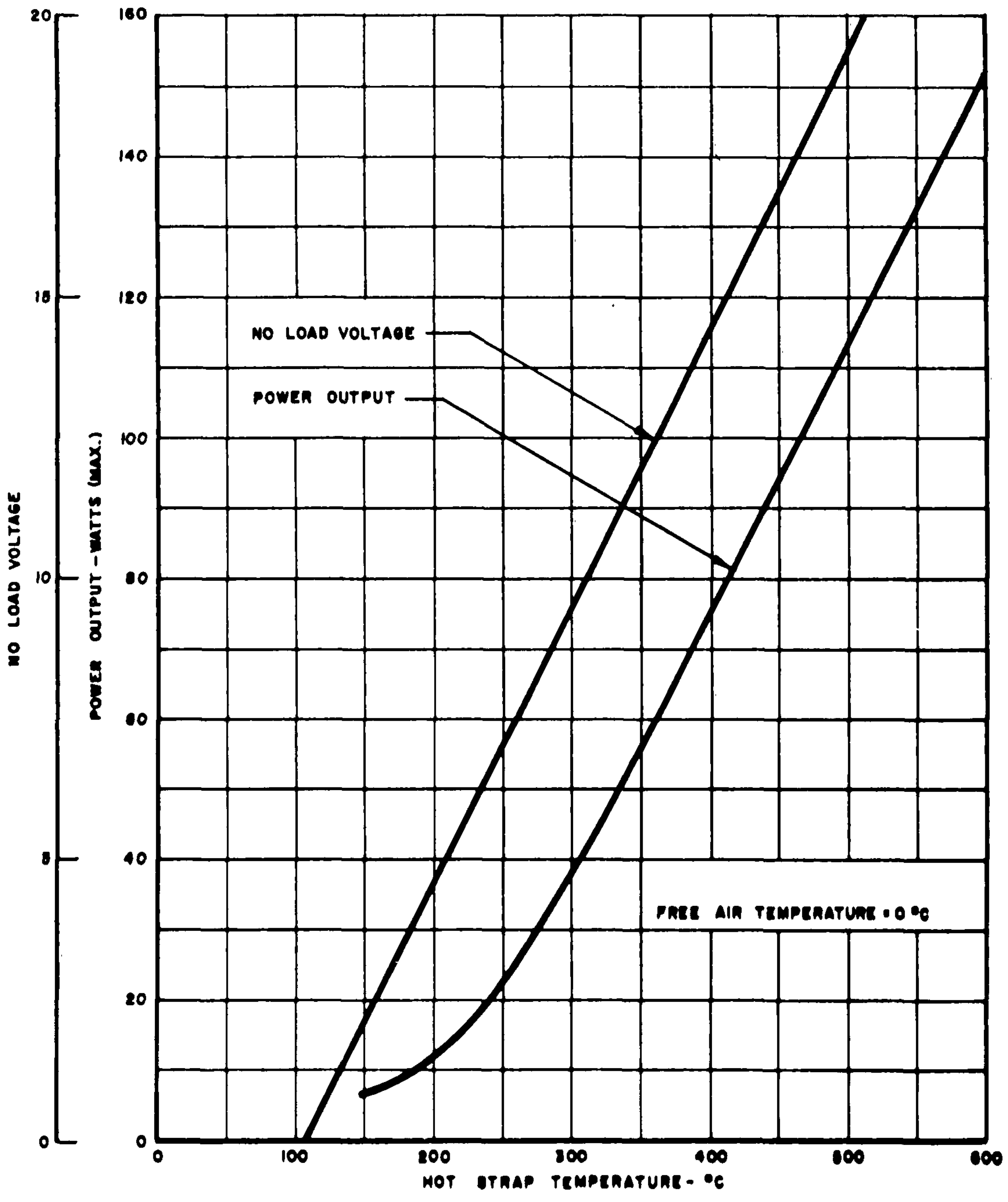

NO LOAD VOLTAGE
POWER OUTPUT -WATTS (MAX.)
NO LOAD VOLTAGE
POWER OUTPUT
FREE AIR TEMPERATURE = 0 °C
HOT STRAP TEMPERATURE - °C
0
5
10
15
20
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600

FIG. 17

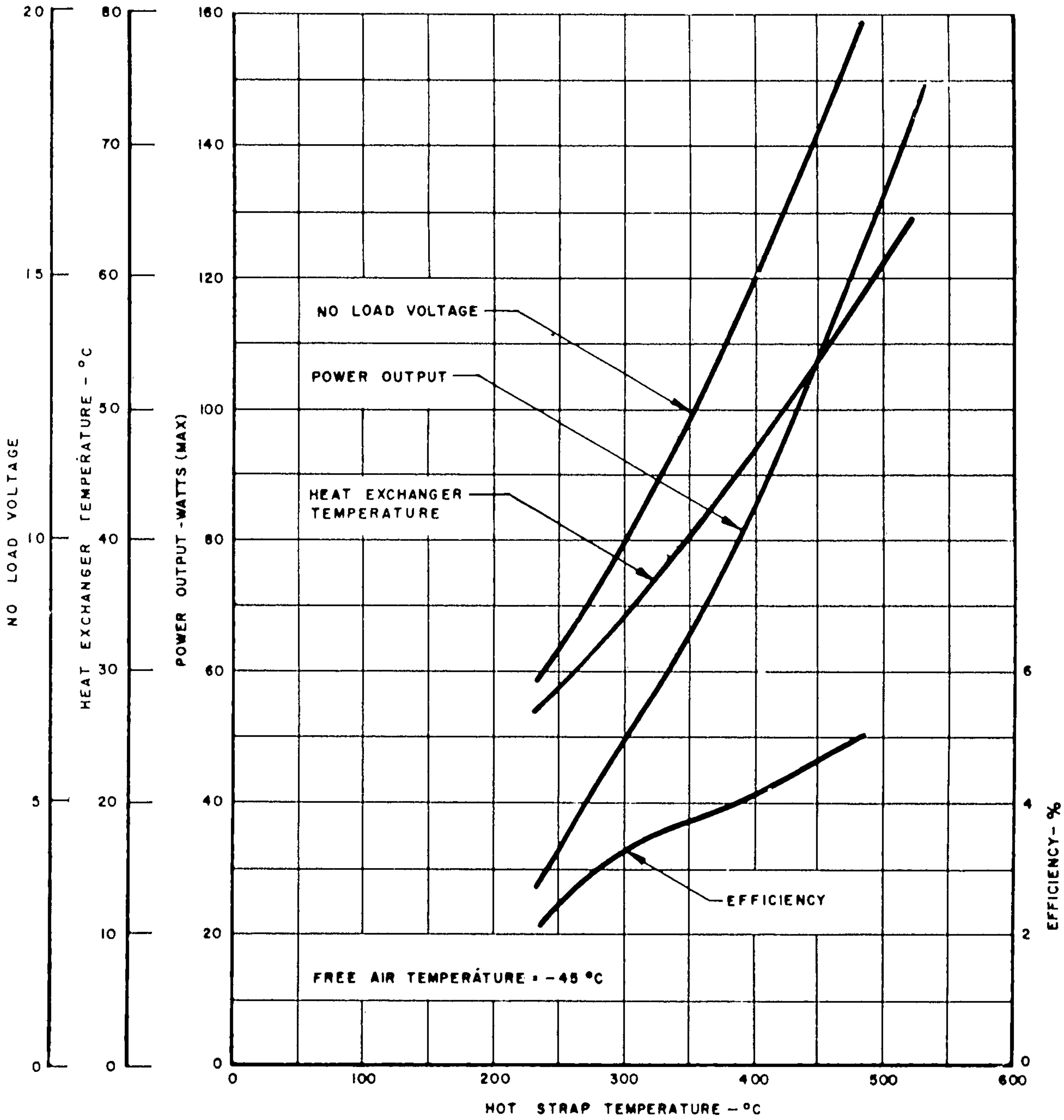

NO LOAD VOLTAGE
HEAT EXCHANGER TEMPERATURE - °C
POWER OUTPUT - WATTS (MAX)
EFFICIENCY - %
NO LOAD VOLTAGE
POWER OUTPUT
HEAT EXCHANGER TEMPERATURE
EFFICIENCY
FREE AIR TEMPERATURE = -45 °C
HOT STRAP TEMPERATURE - °C

FIG. 18

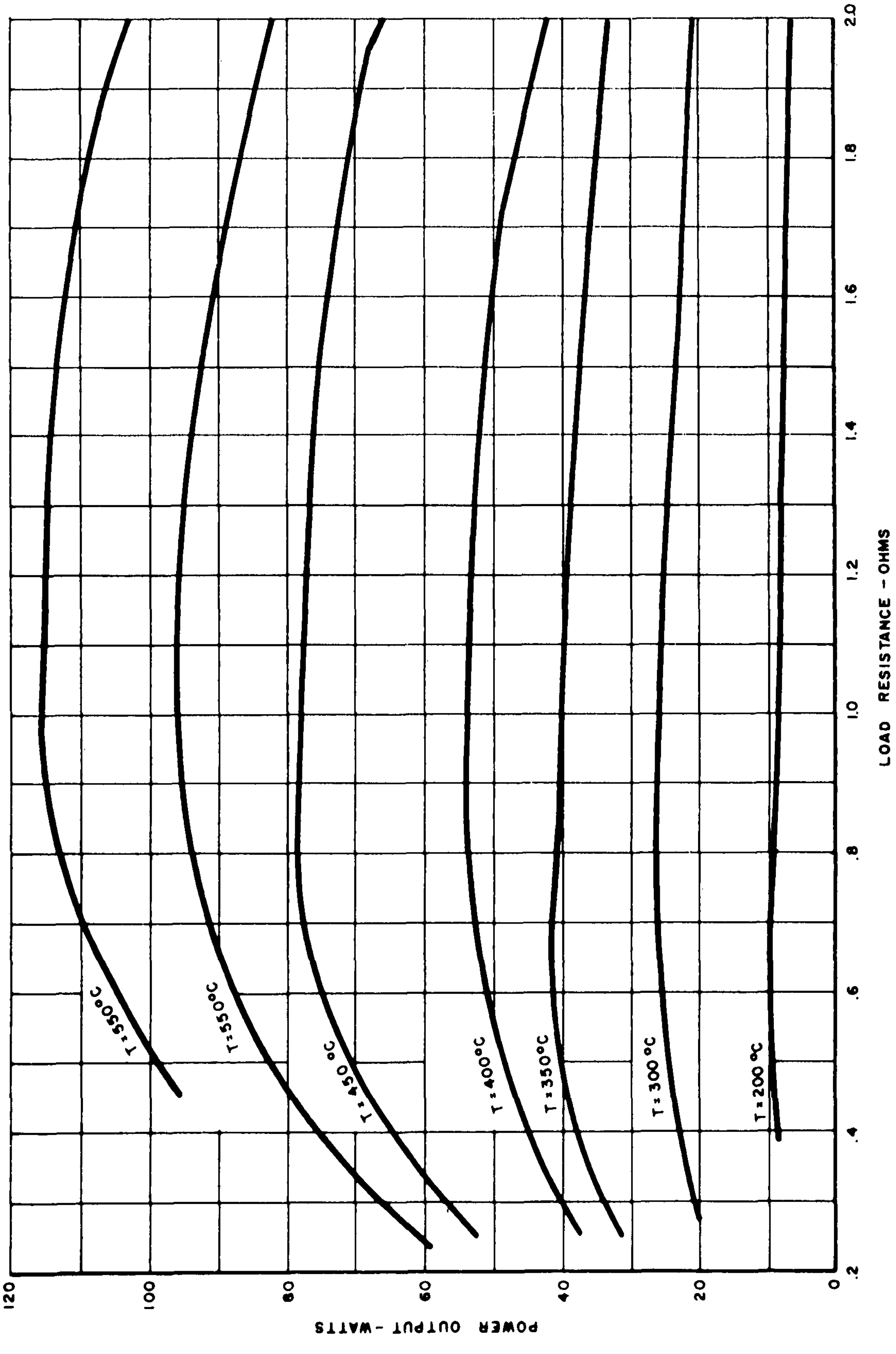

POWER OUTPUT - WATTS
0
20
40
60
80
100
120
LOAD RESISTANCE - OHMS
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
T=550°C
T=550°C
T=450°C
T=400°C
T=350°C
T=300°C
T=200°C

FIG. 19

References:

1. Westinghouse Thermoelectricity Quarterly Progress Report - U. S. Navy - BuShips - Contract No. NObs-84317 - Period Covered: September 11, 1961 - November 11, 1961

2. U. S. Air Force - Contract No. AF30(6C2)-1875

3. Moreland, W. C., Corry, T. M., and Spira, G., TAP-100 Thermoelectric Generator, Westinghouse New Products Research Laboratories, Report No. 9091-F-6930-1-(1)

4. McCormick, J. E., Performance of TAP-100 Thermoelectric Converter, U. S. Air Force, Rome Air Development Center, Report-RADC-TN-61-26

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Unclassified Report

This report describes the development and performance of a 100-watt thermoelectric generator designated NAP-100 (Nuclear Auxiliary Power). The work was performed for the US Air Force under Contract No. AF 30(602)-1875. The delivery of the generator fulfills the second phase of the contract which required the development and construction of an isotopic fuel thermoelectric generator rated at 100 watts electrical output. Construction details and generator performance data are given in this report for the NAP-100 generator. The generator was delivered on December 7, 1960.

1. Generators
2. Heat transfer
3. NAP
4. Power plants
5. Power supplies
6. Radioisotopes
7. Thermal conductivity
8. Thermocouples

I. AFSC Project 6185, Task 618503
II. Contract AF 30(602)1875
III. Westinghouse Electric Corp, New Products Labs, Cheswick, Pa.
IV. G. Spira, T. M. Corry
V. Secondary Rpt No. 9161-01107-203(1)
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